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EFFECTS OF IRRIGATION DRAINWATER CONTAMINANTS ON WILDLIFE

U.S. FISH AND WILDLIFE SERVICE
PATUXENT WILDLIFE RESEARCH CENTER
LAUREL, MARYLAND 20708

This report presents the results of a study conducted for the Federal-State Interagency San Joaquin Valley Drainage Program. The purpose of the report is to provide the Drainage Program agencies with information for consideration in developing alternatives for agricultural drainage-water management. Publication of any findings or recommendations in this report should not be construed as representing the concurrence of the Program agencies. Also, mention of trade names or commercial products does not constitute agency endorsement or recommendation.

The San Joaquin Valley Drainage Program was established in mid-1984 as a cooperative effort of the U.S. Bureau of Reclamation, U.S. Fish and Wildlife Service, U.S. Geological Survey, California Department of Fish and Game, and California Department of Water Resources. The purposes of the Program are to investigate the problems associated with the drainage of irrigated agricultural lands in the San Joaquin Valley and to formulate, evaluate, and recommend alternatives for the immediate and long-term management of those problems. Consistent with these purposes, Program objectives address the following key areas: (1) Public health, (2) surface- and ground-water resources, (3) agricultural productivity, and (4) fish and wildlife resources.

Inquiries concerning the San Joaquin Valley Drainage Program may be directed to:

San Joaquin Valley Drainage Program
2800 Cottage Way, Room W-2143
Sacramento, California 95825-1898

SUMMARY REPORT

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INTRODUCTION

In March 1986, the U.S. Fish and Wildlife Service (USFWS) and the U.S. Bureau of Reclamation entered into an intra-agency agreement (6-AA-20-04170) for the purpose of supporting research on the effects of agricultural drainwater contaminants on fish and wildlife populations. The agreement initiated a multi-year research effort to be conducted by USFWS research centers in support of the San Joaquin Valley Drainage Program. The Patuxent Wildlife Research Center had responsibility for five major areas of research, hereafter referred to as Work Units, under this agreement. Each Work Unit addressed specific aspects of the exposure of wildlife to drainwater pollutants and their biological effects using field and laboratory methods, but all Work Units were inter-related to provide a comprehensive approach to understanding the impacts of drainwater contaminants on wildlife populations.

This report summarizes findings and main conclusions from all five Work Units. Details on experimental methods, as well as tables and figures of results are not included in this report. The reader is referred to the publications and other reports listed in the Products section for more details. For the sake of consistency, all concentrations of selenium and other contaminants in eggs and tissues are presented on a dry weight basis.

There is also a section on Research Needs that summarizes the additional research required to better understand drainwater hazards to wildlife.

WORK UNIT REPORTS

Work Unit 120.39 Accumulation and loss rates of selenium in waterfowl.

Objectives

1. To determine the effects of variables, including duration and concentration of exposure, on the accumulation of selenium by waterfowl.
2. To determine the relative accumulation of organic and inorganic forms of selenium by birds, and to observe gross differences in loss rates.
3. To determine the rate of loss of a sublethal, but potentially harmful, body burden of selenium in waterfowl.
4. To relate accumulation and loss rates to known patterns of movement in waterfowl and other migratory birds.

Findings

Accumulation and Loss Rate Studies

Adult female mallards (*Anas platyrhynchos*) were fed a diet containing 10 ppm selenium in the organic form of selenomethionine (Heinz et al., 1990). The diet fed to the ducks in this and all other experiments was a commercial duck mash that contained only 7 to 10 percent water. Therefore, dietary concentrations for mallards are always presented on what is very close to a dry weight basis. A small number of adult male mallards was included in this study to compare results to females. The ducks were fed the selenium-treated diet for 6 weeks, followed by 6 weeks of a control diet. Birds were sacrificed each week, and selenium was measured in liver and muscle to enable graphing of the accumulation and loss patterns of selenium.

There were no marked differences between males and females in accumulation and loss of selenium in tissues. Mathematical equations were derived to describe the accumulation and loss of selenium in females. The equations predicted peak concentrations of 25 and 31 ppm selenium for liver and muscle. Liver normally contains higher concentrations of selenium than muscle, but at a fairly low dietary concentration of 10 ppm selenium this apparently is not always the case. In a separate study, breeding female mallards fed 10 ppm selenium as selenomethionine also had slightly higher levels of selenium in muscle than in liver (Heinz et al., 1987). The estimated times to reach 95 percent of the projected peaks were 7.8 days for liver and 81.0 days for muscle. In the loss phase of the experiment, selenium was calculated to have a half-time of 18.7 days for liver and 30.1 days for muscle.

In an additional study to measure loss of selenium from mallards, adult females were fed increasing concentrations of selenomethionine until some birds died (Heinz et al., 1990). The objective was to build up maximum selenium levels in the survivors so that loss could be measured over the greatest possible range of selenium concentrations. Liver reached a peak of 77 ppm selenium and muscle reached a peak of 25 ppm selenium, suggesting that, at high dietary concentrations of selenium, liver does accumulate more selenium than muscle. The equation describing loss of selenium from liver followed a two-compartmental model, meaning that loss was rapid at first, followed by a gradual slowing down of loss. Initially, one-half of the selenium was lost from liver in only 3.3 days, but subsequent half-times lengthened to 3.9, 6.0, and 45.1 days. For muscle and blood, simple, one-compartmental models sufficed; the half-times were 23.9 and 9.8 days, respectively. Results from the two experiments described above show that selenium is quickly built up and quickly lost from mallard tissues, especially in the liver, which is an active site of selenium metabolism.

Another study was conducted to measure the accumulation and loss of selenium in eggs. Laying female mallards were placed on a diet containing 15 ppm selenium as selenomethionine (G.H. Heinz, unpublished data). After 20 days on treatment, they were returned to a control diet. After only one to two weeks on the selenium diet, selenium levels in eggs peaked at about 68 ppm. Once returned to a control diet, selenium in eggs dropped within about one week to less than 17 ppm. This study again demonstrated that selenium is rapid in its buildup and loss in birds.

Toxicity of Organic and Inorganic Selenium

Selenium accumulation in young and adult mallards was found to be dependent upon the chemical form fed. When adult female mallards were fed 16 ppm selenium, as selenomethionine, livers contained a mean of 25 ppm selenium and eggs a mean of 61 ppm selenium (Heinz et al., 1989). However, when the diet contained 16 ppm selenium, as selenocystine (another organic form), only 5.4 and 1.9 ppm selenium accumulated in liver and eggs. When mallards ducklings were fed 40 ppm selenium, as selenomethionine, for the first 6 weeks of life, livers contained a mean of 231 ppm selenium, contrasted to only 9.5 ppm in the livers of ducklings fed 40 ppm selenium as sodium selenite, an inorganic form (Heinz et al., 1988).

Selenomethionine is reported to substitute in protein for the amino acid methionine. This substitution may, in part, explain the greater ability of selenomethionine to accumulate in tissue compared to selenocystine or sodium selenite. In addition, there could be differences in absorption and metabolism of the different chemical forms of selenium.

Work Unit 120.40 Determination of maximum safe levels of selenium and other contaminants for waterfowl under conditions of chronic exposure.

Objectives

1. Determine the threshold levels of selenium and boron incorporated into the diet that cause effects on survival and reproduction in waterfowl when fed throughout the reproductive season.
2. Determine the threshold levels for selenium and boron in the diet that cause effects on survival and health of ducklings from hatching to attainment of adult size.
3. Determine the maximum safe level of selenium in the diet that can be tolerated by adult birds in conditions corresponding to the over-wintering period.

Findings

Toxic Threshold of Selenium on Reproduction

Adult mallards were fed a control diet or diets supplemented with 1, 2, 4, 8, and 16 ppm selenium as selenomethionine (Heinz et al., 1989). Another group was fed 16 ppm selenium as selenocystine. Females fed the control diet produced a mean of 8.1 ducklings when duckling survival was followed for 6 days. Females fed 8 ppm selenium produced only 4.6 ducklings per female, and females fed 16 ppm selenium as selenomethionine did not produce any young that survived to 6 days. Diets containing 1, 2, or 4 ppm selenium had no significant effects on reproduction. Selenocystine, at 16 ppm selenium in the diet, also had no significant effect on reproduction. Selenium in eggs of females fed 4 ppm selenium, the highest no-effect level, averaged 12 ppm selenium. In eggs of females fed 8 ppm selenium, the lowest effect level, there was an average of 37 ppm selenium. In a related study, dietary exposure to 3.5 ppm selenium (as selenomethionine) did not impair mallard reproduction, but 7 ppm did (G.J. Smith, unpublished data).

Therefore, from laboratory studies, it appears that the dietary threshold for reproductive impairment falls between 4 and 7 ppm selenium when fed as selenomethionine.

Two other species, the black-crowned night-heron (Nycticorax nycticorax) and the screech owl (Otus asio), were found to be less sensitive to the reproductive effects of selenium. Reproduction of black-crowned night-herons was unaffected by a dietary concentration of about 10 ppm selenium as selenomethionine (Smith et al., 1988). Mallards fed 10 ppm selenium, by contrast, experienced an 80 percent decrease in number of ducklings produced compared to controls (Heinz et al., 1987). Part of the difference in sensitivity may lie in the fact that selenium residues in heron eggs (11 ppm) were lower than in mallard eggs (16 ppm) when both species were fed the same dietary concentration of selenomethionine.

Screech owls fed about 10 ppm selenium as selenomethionine experienced no reproductive impairment (S.N. Wiemeyer, unpublished data). When fed 30 ppm selenium, food consumption of adults temporarily fell off and two adults died. Only one of 17 eggs laid by owls fed 30 ppm selenium hatched, and the hatchling died within a day. Selenium analyses from this study have not yet been completed.

Mallards, therefore, appear to be more sensitive to selenium poisoning than screech owls or black-crowned night-herons. Studies at other laboratories suggest that the chicken may be more sensitive to selenium than the mallard. Although the underlying basis for the species differences in sensitivity to selenium are not known, our results raise the question of whether there might be other wild birds that are more sensitive than the mallard.

Reproductive Success After Winter Exposure to Selenuim

A study was conducted to determine if migratory birds overwintering in a selenium-contaminated area could accumulate, retain, and carry enough selenium burden to the breeding area to impair reproduction (G.H. Heinz, unpublished data). To address this question, adult mallards were fed 15 ppm selenium, as selenomethionine, for 21 weeks during winter. Had such a diet been continued throughout the breeding season, reproduction would have been completely eliminated, based on results from past studies (Heinz et al., 1987; Heinz et al., 1989). However, at the onset of the breeding season, selenium was removed from the diet to simulate migration to a clean breeding area. Females that began egg laying just two to three weeks after the switch to the control diet had normal reproduction compared to birds that had always been fed a control diet. Since birds would normally take longer than two to three weeks to migrate to their breeding grounds and begin egg laying, it is unlikely there would be a harmful carryover effect of selenium contamination from the wintering area. The reason for the quick return to normal reproduction was a rapid loss of selenium from the bodies of the females and, consequently, little selenium incorporated into their eggs.

Lethal and Sublethal Effects of Selenium

In addition to studies on reproductive effects of selenium, several studies examined lethal and sublethal effects on young and adult birds. Adult mallards were fed 0, 10, 20, 40, or 80 ppm selenium as selenomethionine for 16 weeks over winter (G.H. Heinz, unpublished data). Mortality was 0, 0, 25, 95, and 100 percent, respectively. After one week on treatment, body weights were significantly depressed by 20, 40, and 80 ppm selenium, but at no time during the study did 10 ppm selenium affect weight. Four weeks after being switched back to a control diet, ducks that had been fed 20 ppm selenium returned to normal weight. In a companion study conducted in the spring and summer, 0, 10, 20, 40, and 80 ppm selenium caused 0, 0, 5, 15, and 100 percent mortality (P.A. Albers, unpublished data). A comparison of results from both studies suggests that adult mallards are more sensitive to selenomethionine during cold weather than warm weather. In the latter study, birds fed 40 ppm selenium had a significantly delayed molt.

The health and survival of day-old mallards was determined when a control diet or diets containing 10, 20, 40, or 80 ppm selenium, as sodium selenite or selenomethionine, was fed for 6 weeks (Heinz et al., 1988). At 80 ppm, selenium caused 97.5 percent mortality as sodium selenite and 100 percent mortality as selenomethionine. At 40 ppm, these two chemical forms of selenium caused 25 and 12.5 percent mortality, respectively. Neither form of selenium caused any mortality at 10 or 20 ppm. At 20 ppm, food consumption and growth were reduced, but these reductions were not caused by 10 ppm.

Sublethal physiological effects were documented in several studies. Selenium caused sublethal alterations of glutathione metabolism. The lowest dietary concentration of selenium fed to laying mallards that caused biochemical effects in their hatchlings was 5.4 ppm, as selenomethionine (Hoffman and Heinz, 1988). A diet of about 10 ppm selenium, as selenomethionine, caused changes in glutathione metabolism and lipid peroxidation in black-crowned night-herons and screech owls (Smith et al., 1988; Hoffman, unpublished data). Elevated plasma glutathione peroxidase activity was observed in adult mallards fed 2 ppm selenium, as selenomethionine (D.J. Hoffman, unpublished data). These findings are indicative of changes in organs such as the liver; they may be viewed as early signs of selenium toxicity in birds.

Behavioral effects of selenium toxicity were studied in female mallards were fed 1, 2, 4, and 8 ppm selenium as selenomethionine (Heinz and Gold, 1987). Avoidance behavior was measured in an apparatus designed to frighten birds in a way that would simulate fleeing from a predator. None of the selenium treatments affected the behavior of the offspring.

Arsenic and Boron Toxicity

Additional studies also were conducted to measure the toxicity of boron and arsenic to mallards. Adult mallards were fed 0, 30, 300, or

1000 ppm boron as boric acid (Smith and Anders, 1989). Hatching success of fertile eggs was 46.3 percent for females fed 1000 ppm boron, compared to 88.5 percent for controls. Hatching weights of ducklings were reduced by 300 and 1000 ppm boron, and weight gain over 21 days was significantly lower in the groups fed 30, 300, and 1000 ppm boron.

In a study of boron toxicity, day-old mallard ducklings were fed a control diet or diets containing 100, 400, or 1600 ppm boron as boric acid for 10 weeks (Hoffman et al., 1990). The diet containing 1600 ppm boron caused 10 percent mortality and a decrease in growth. Hematocrit and hemoglobin were lower in ducklings fed 1600 ppm boron, and plasma triglyceride was elevated in all three boron treatments.

Boron at 1600 ppm and arsenic at 300 ppm altered activity schedules of ducklings, including increased time resting and decreased time in alert behaviors and time spent in water (M.R. Whitworth, unpublished data). Such aberrations in behavior could affect survival in the field; for example, by increasing the risk of predation.

Arsenic, as sodium arsenate, was fed to day-old mallards at 0, 30, 100, or 300 ppm for 10 weeks (Camardese et al., 1990). At all three dietary levels, arsenic resulted in decreased growth of female ducklings. Only the 300 ppm arsenic diet decreased the growth of males. Food consumption was reduced by 300 ppm arsenic. Among physiological measurements, plasma sorbitol dehydrogenase activity and plasma glucose were higher in ducklings fed 300 ppm arsenic compared to controls.

Work Unit 120.42 Accumulation and effects of contaminants in agricultural wastewater on wintering and migrating waterfowl in the San Joaquin Valley.

Objectives

1. To determine movements and length of stay of individual waterfowl in the San Joaquin Valley during the winter season.
2. Sample the five most intensively used sites for concentrations of selenium and other elements in aquatic vegetation and invertebrates.
3. Assess the short-term and long-term effect of these contaminants on waterfowl recruitment and mortality based on the results of field and interpretive studies.

Findings

Field studies that were originally planned to achieve these objectives could not be conducted because of funding limitations. As an alternative, we considered the possibility of conducting a computer analysis of movement patterns and winter-use of habitats in the San Joaquin Valley by northern pintails (Anas acuta). Banding and recovery data for pintails banded in a 25 square-mile area of western Merced County, California, were obtained from the U.S. Fish and Wildlife Service's Bird Banding Laboratory.

Previous publications, especially the following ones by W.C. Rienecker, have discussed the migration, distribution, and survival of pintails banded in California:

1. Migration and distribution of northern pintails banded in California. California Fish and Game 73:139-155, 1987.
2. Survival and recovery rate estimates of northern pintail banded in California, 1948-79. California Fish and Game 74:230-237, 1987.

3. Additional notes on migrational distribution of northern pintail banded in California. California Fish and Game 74:61-63, 1988.

These reports, however, have not addressed the questions posed by the above objectives, nor could we answer those questions using the available banding data. In addition, the second objective, to evaluate foods of pintails at those sites most heavily used by the birds, could not be achieved through an analysis of band returns.

A recent analysis of 1980-87 mid-winter waterfowl counts in the Southern San Joaquin Valley by the U.S. Fish and Wildlife Service's Northern Prairie Wildlife Research Center has identified pre-irrigated croplands as the habitat supporting the highest density of wintering pintails (D.A. Barnum, unpublished data). Drainwater evaporation ponds supported the lowest density among five habitat types.

It appears that the third objective of this Work Unit is the most critical. The short- and long-term effects of contaminants in agricultural wastewater on waterfowl reproduction and mortality may be best evaluated, given the current financial status of the drainwater studies, by interpretation of laboratory studies in conjunction with knowledge of migration and breeding patterns. One completed study (Work Unit 120.40) showed that mallards fed diets containing 15 ppm of selenium as selenomethionine for 21 weeks were capable of normal reproduction within about two weeks after being switched to an uncontaminated diet (G.H. Heinz, unpublished data). These results confirm findings of previous studies with domestic poultry.

Although about 2 million pintails winter in California, most of the breeding by this species occurs in prairie Canada and Alaska. According to Bellrose (1976; Ducks, Geese, & Swans of North America, pp. 270-272), pintails begin moving northward in late January or early February and nest in April and May. Thus, even if the ducks had been exposed for a prolonged period to elevated dietary concentrations of selenium, for example, it is likely that they would have excreted the selenium sufficiently that reproduction would not be affected. Although this would not be true for birds wintering and breeding in the same contaminated area, available data indicate that most pintails leave California to breed farther north. As long as the birds do not die on the wintering areas and they arrive on the breeding areas with adequate body mass and composition for breeding, they should not be adversely affected by selenium acquired during the winter. This assumes that sublethal exposure to selenium will not affect migration behavior; no studies to measure effects of selenium on migration behavior have been carried out. Information concerning other contaminants is less readily available, but selenium is likely the primary contaminant adversely affecting waterfowl reproduction in the San Joaquin Valley.

Work Unit 120.43 Development of predictive capability in assessing impacts of agricultural drainwater on wildlife species.

Objectives

1. Determine what concentrations of common drainwater contaminants in which tissues are associated with degrees of reproductive impact on populations of birds and mammals.
2. Determine what concentrations of common drainwater contaminants are associated with mortality in populations of birds and mammals.
3. Develop any other indices of biological changes associated with drainwater contaminants.

Findings

Studies in California

The Grasslands of western Merced County, California, is an area that has historically received selenium-contaminated agricultural drainwater. The reproductive success of nesting ducks and shorebirds was studied there during 1986-1987 and at a reference site in 1987 (Hothem, 1989; Hothem and Welsh, in review). Nest success and cause-specific failure rates were estimated, and these parameters and hatchability were compared between sites and years. Nest success and causes of failure varied by species, site, and year. Eggs were collected and analyzed for selenium, boron, and arsenic, and correlations between contaminant concentrations and nesting success were tested. Concentrations of arsenic and boron were both lower than those that have been shown to adversely affect avian reproduction. Embryonic abnormalities were not observed in the Grasslands, and levels of selenium, while generally higher than those found in uncontaminated areas, were much lower than those found to cause severe reproductive impairment at nearby Kesterson Reservoir. The reduction in the use of drainwater in the Grasslands starting in 1985 apparently reduced contamination in foods used by birds to a level such that reproduction was not adversely affected to a significant degree.

Since the early 1970's about 7,000 acres of drainwater evaporation ponds were established in the San Joaquin Valley's southernmost watershed, the Tulare Basin. Located about 100 miles south of Kesterson Reservoir, several of these ponds were assessed for contaminant effects on breeding waterbirds during 1987-89 (Ohlendorf and Skorupa, 1989; Skorupa and Ohlendorf, in review; J.P. Skorupa, unpublished data). Unlike Kesterson Reservoir, which was managed to maximize wildlife habitats, Tulare evaporation ponds usually lack emergent aquatic vegetation (such as bulrush or cattails) or any significant terrestrial plant cover and are managed solely for wastewater disposal. Nonetheless, more than 20 species of birds have been found breeding on evaporation ponds and some species occur on the ponds at higher densities than at any of the national wildlife refuges or other wildlife management areas in the San Joaquin Valley (Schroeder et al., 1988; U.S. Geol. Survey Water-Res. Invest. Rpt. 88-4001; J.P. Skorupa, unpublished data). Abnormally high rates of embryo deformity were discovered in eight species of birds, and in all cases were associated with abnormally high levels of selenium in the eggs. In addition, most cases of depressed egg hatchability were also associated with selenium-contaminated eggs. These results confirmed that earlier findings from Kesterson Reservoir were indicative of a general syndrome and not just a unique isolated case.

Mean selenium concentration in black-crowned night-heron eggs from Salton Sea (approximately 5.5 ppm) was significantly higher than in eggs from three locations in the San Joaquin Valley, and in great egret (Casmerodius albus) eggs from Salton Sea (Ohlendorf and Marois, in press). Exceptionally high concentrations of DDE were found in black-crowned night-heron (geometric mean of approximately 43 ppm) and great egret (approximately 81 ppm) eggs collected from the Imperial Valley (Salton Sea), California in 1985. DDE concentrations in 14 of the 87 (16 percent) randomly selected night-heron eggs from six colonies (two in San Francisco Bay, three in the San Joaquin Valley, and one at Salton Sea) were higher than those associated with reduced reproductive success of night-herons (approximately 40 ppm; Custer et al., 1983, Auk 100:699-710; Henny et al., 1984, J. Wildl. Manage. 48:1-13). In addition, mean shell thickness of night-heron eggs collected from the San Joaquin Valley and from San Francisco Bay during 1982-1984 was significantly less than pre-DDT thickness and was negatively correlated with DDE concentration.

In February-March 1986, eight raccoons (Procyon lotor) were collected at Kesterson Reservoir, and four raccoons were collected at the nearby Volta Wildlife Area (Clark, 1987). Selenium concentrations in Kesterson raccoons averaged 19.9 ppm in liver, 28.3 ppm in hair, 21.6 ppm in feces, and 14 ppm in blood and exceeded Volta concentrations by 12, 30, 21, and 10 times, respectively. Selenium concentrations in hair provided the strongest statistical separation between study areas. Hemoglobin levels in two Kesterson raccoons equalled levels reported in rats with selenium-induced anemia, but the raccoons showed no illness. Amyloidosis (an abnormal infiltration of organs with proteins) in one Kesterson raccoon may have been selenium-induced. However, based on this sample of 12 raccoons, there was no clear evidence that contamination had negative effects on raccoons inhabiting Kesterson.

Carson Lake, Nevada

In white-faced ibis (*Plegadis chihi*) nesting at Carson Lake, Nevada, during 1985 and 1986, selenium and mercury were accumulated on the breeding grounds, but concentrations in eggs did not reach levels sufficient to impact the production of 7-10-day-old young (Henny and Herron, 1989). Potential selenium and especially mercury accumulation during the remainder of the summer were high, but actual effects on growing young and adults remain unknown. Mercury and selenium are known to counteract each other's toxicity. However, DDE concentration was related to fewer young produced per nesting attempt, fewer young produced per successful nest, and eggshell thinning. As DDE in eggs increased to >14 ppm (approximate dry weight conversion from wet weight value), and especially >27 ppm, productivity decreased significantly and the incidence of cracked eggs increased. Assuming that 14 ppm DDE is the critical residue level, 40 percent of the nesting population in 1985 and 1986 was adversely impacted by DDE, with a nest loss of 20 percent of the population's expected production (to about 10 days old). Most eggs containing exceptionally high DDE levels (approximately 27-98 ppm) also had substantial amounts of DDT, which implies recently-used DDT as the source. No evidence of breeding ground DDE-DDT contamination was found. The white-faced ibis winter in Mexico, mostly in the interior agricultural region. Concentrations of DDE-DDT in ibis eggs, unlike most other wading bird species from the Great Basin, did not decline during the last decade. Other organochlorine contaminants were generally low and detected in $\leq$ 33 percent of the eggs.

Martin Lake, Texas

In 1986, a study was initiated to assess the levels and effects of selenium in birds nesting at Martin Lake, Texas (K.A. King, unpublished data). Fish kills had occurred there from September 1978 to May 1979, when selenium-laden ash was discharged from a lignite-fired power plant into the 5,000-acre lake, used as a cooling reservoir. Field studies focused on red-winged blackbirds (Agelaius phoeniceus) and barn swallows (Hirundo rustica) to determine if selenium accumulations through the aquatic food chain were sufficiently elevated to jeopardize reproduction. Both species occasionally feed on aquatic insects that may have emerged from selenium-contaminated sediments. Adult blackbirds collected at Martin Lake contained significantly higher levels of selenium in kidney tissues (33 ppm) than blackbirds from a nearby control area (7.7 ppm). Selenium in Martin Lake blackbird eggs (11 ppm) averaged over four times the levels found in control eggs (2.4 ppm). Hatching success of blackbird eggs at the power plant reservoir (26 percent) was less than half that (56 percent) of controls. Swallows also had significantly higher selenium levels in kidney tissues (15 ppm) than controls (5.9 ppm) and the mean level of selenium in 10 swallow eggs from Martin Lake (3.3 ppm) was about twice that of controls (1.7 ppm). However, hatching success of barn swallows was similar at the two areas. Although the dominant valence state of dissolved selenium in Martin Lake was unknown, avian dietary exposure should primarily have been to organoselenium (Hamilton et al. 1990, Environ. Toxicol. Chem. 9:347-358).

Stillwater Wildlife Management Area, Nevada and Malheur National Wildlife Refuge, Oregon and Other Areas

Studies of ducks and other waterbirds were conducted at Stillwater Wildlife Management Area (WMA), Nevada, in 1986-88; Malheur National Wildlife Refuge (NWR), Oregon, in 1986-87; and at several sites in the vicinity of Seedskadee NWR, Wyoming, in 1988; and at Benton Lake NWR, and Freezeout Lake, Montana, in 1989 (C.J. Henny, unpublished data). Two eggs were collected from each duck nest for artificial incubation and one egg was taken from each duck or other waterbird nest for chemical analyses. Reproductive success of these nests also was determined. Findings at Malheur NWR indicated there was no apparent effect of drainwater contaminants on reproductive success of birds. Fluctuating water levels and high predation contributed to poor nesting success at several sites. However, at some sites, including Stillwater WMA and Ouray NWR, there were elevated concentrations of selenium, mercury, and/or DDE in birds or their eggs as well as apparent contaminant-related effects in some of the bird species that were studied. Embryo deformities were found at Stillwater WMA, Ouray NWR, and Benton Lake NWR.

Synthesis of Field Data and Interpretation

Analysis of field data collected during the breeding season in the San Joaquin Valley and elsewhere in the western United States shows that the mean concentration of selenium in random samples of bird livers is normally below 10 ppm (all concentrations on dry weight basis) which is the 85th percentile value for 86 means from uncontaminated reference sites (J.P. Skorupa, unpublished data). Likewise, the mean concentration of selenium in random samples of bird eggs is normally below 2.8 ppm, the 85th percentile for 74 means from reference sites (Skorupa and Ohlendorf, in review). Mean selenium concentrations in waterbird eggs from Tulare drainwater ponds are as high as 75 ppm, or about 25 times normal background. Assessments of embryo condition at reference sites indicate that overt multiple malformations are normally exhibited by less than 1 embryo per 1,000 examined (J.P. Skorupa, unpublished data). Thus, the detection of even one embryo with obvious multiple deformities in a normal reconnaissance sample of

10 to 50 embryos would be sufficient to justify further investigation. In the Tulare Basin, the observed incidence of overt multiple malformations often exceeds 10 percent, or more than 100 times normal background (J.P. Skorupa, unpublished data).

At a population level of analysis, there are clear dose-response relationships between tissue selenium (liver or egg) and the observation of one or more deformed embryos during field assessments (Skorupa and Ohlendorf, in review). For example, deformities were detected among only 3 of 55 (5.5 percent) populations assessed for embryo condition when mean selenium concentration in eggs was less than 3 ppm (i.e., at background levels). In contrast, deformities were detected among 9 of 10 (90 percent) populations with mean egg selenium greater than 48 ppm. Overall, the data show a very high risk of embryonic deformity when a population's mean egg selenium exceeds 20 ppm and when mean liver selenium exceeds 30 ppm (during the egg-laying period) (J.P. Skorupa, unpublished data). Thus, population means below 10 ppm for livers and 3 ppm for eggs usually are not associated with biological risk, whereas population means above 30 ppm for livers and 20 ppm for eggs usually are. Biological implications of population means between 10 and 30 ppm for livers and between 3 and 20 ppm for eggs cannot be interpreted with high confidence without a detailed field study of reproductive performance. In the Tulare Basin, population means exceeding 20 ppm selenium in eggs have been measured from ponds comprising 63 percent of the 4,190 acres studied in 1987-89 (J.P. Skorupa, unpublished data).

Based on data from Kesterson Reservoir and the Tulare Basin, field estimates of selenium bioaccumulation in eggs, via dietary exposure, appear to correspond closely with experimental results if the wild birds restrict their feeding to a discrete contaminated site. It is predicted from field data that the dietary threshold for adverse reproductive effects among ducks is 5.6 ppm (J.P. Skorupa, unpublished data). This estimate is consistent with the estimate of 5.4 ppm derived from experimental studies of the physiology of mallard embryos (Hoffman and Heinz, 1988) and also falls within the 4 to 7 ppm span identified by experimentally feeding selenomethionine to mallards (Heinz et al., 1989; G.J. Smith, unpublished data). There have been no studies to identify the chemical forms of selenium in waterfowl foods in selenium-contaminated areas, but fisheries research has shown that selenomethionine is an excellent model for natural dietary exposure to selenium-contaminated invertebrates (Hamilton et al., 1990, Environ. Toxicol. Chem. 9:347-358).

In wide-ranging species of birds such as ducks, dietary exposure to selenium during the breeding season may be influenced by the landscape mosaic surrounding a contaminated site. For example, Kesterson Reservoir occurred within a rich mosaic of relatively uncontaminated neighboring wetlands. Thus, ducks nesting at Kesterson had choices for habitat use that would have reduced their dietary exposure to selenium. By contrast, drainwater evaporation ponds in the Tulare Basin are isolated within an agricultural landscape mostly devoid of "clean" wetlands during the spring. Based on comparisons with a highly sedentary breeder (eared grebe, _Podiceps_ _nigricollis_), Kesterson duck eggs realized only 15 to 30 percent of the site potential for bioaccumulating selenium, whereas, Tulare duck eggs realized 100 percent of their site potentials (Skorupa and Ohlendorf, in review).

Field data collected in the Tulare Basin by the state of California show a strong relationship between water selenium and insect (food-chain) selenium (J. Shelton, unpublished data). By combining these data with experimental data on selenium bioaccumulation in mallard eggs via dietary exposure (Heinz et al., 1989), it is estimated that the waterborne threshold of selenium leading to above-background bioaccumulation in eggs is less than 5.9 parts per billion (ppb). Field data from the Tulare Basin support this prediction. At two sites with waterborne selenium less than 3.2 ppb, waterbird eggs contain background concentrations of selenium. At one site with waterborne selenium varying between 3.1 and 7.2 ppb, waterbird eggs average a little more than twice the background concentration of selenium. The lowest waterborne selenium concentration associated with an elevated incidence of embryo deformities in the Tulare Basin is 15 ppb. All these analyses and direct observations are consistent in suggesting that waterborne concentrations of selenium far below those measured at Kesterson Reservoir can pose environmental hazards (Skorupa and Ohlendorf, in review).

Work Unit 120.77 Interaction of elements in agricultural drainwater in producing effects on waterfowl species.

Objectives

1. Determine the concentration of contaminant elements in selected aquatic vegetation, invertebrates, and fish in wetlands fed by agricultural drainwater in California.
2. Determine the level of impact of these elements, alone or in combination, in short term (60-90 day) studies with adult and young mallards.
3. Evaluate long-term impacts, such as reproductive effects, of selected combinations of elements, including those that showed the most short-term toxicity.

Findings

Contaminants in Vegetation, Invertebrates, and Fish

In 1985, drainwater contaminants were measured in foods of aquatic birds at Kesterson Reservoir (Hothem and Ohlendorf, 1989). Mean selenium concentrations ranged from 26 ppm in waterboatman (Corixidae) to 119 ppm in mosquitofish. Means for selenium in all foods were high enough to have caused the observed reproductive impairment at Kesterson. Boron ranged from less than 100 ppm in invertebrates in certain ponds at Kesterson to 1630 ppm in widgeongrass in one pond. Concentrations of arsenic at Kesterson were all below 2 ppm and were not elevated compared to concentrations at the Volta Wildlife Area (a clean area that did not receive drainwater).

Toxicity of Arsenic, Boron, and Selenium to Birds

In a laboratory study, adult mallards were fed a control diet, a diet containing 10 ppm selenium as selenomethionine, diets containing 25, 100, or 400 ppm arsenic as sodium arsenate, or diets containing 10 ppm selenium plus 25, 100, or 400 ppm arsenic (T.R. Stanley, unpublished data). Hatching success was reduced, as previous studies had predicted, by 10 ppm selenium in the diet. None of the arsenic levels affected hatching, but 400 ppm arsenic decreased fertility, egg weight, shell thickness, and duckling growth. However, the addition of 400 ppm arsenic was antagonistic (counteracted the toxicity of the other chemical) to the 10 ppm selenium; hatching success was better with the selenium plus the arsenic than with the selenium alone. Selenium at 10 ppm caused embryo deformities, but deformities decreased as arsenic additions to the diet increased.

Subsequently, adult mallards were fed a control diet, diets containing 3.5 or 7 ppm selenium as selenomethionine, diets containing 450 or 900 ppm boron as boric acid, or diets containing each combination of selenium and boron (G.J. Smith, unpublished data). For controls, 83.4 percent of fertile eggs hatched. Females fed 7 ppm selenium hatched 50.6 percent of their eggs, and females fed 900 ppm boron hatched 42.7 percent of their eggs. When fed 7 ppm selenium plus 900 ppm boron, hatching success was 42.1 percent; therefore, there was no interaction (lessening or worsening of each others effects) between selenium and boron. Diets containing 3.5 ppm selenium and 450 ppm boron, alone or in combination, did not affect hatching.

Mallard ducklings were also fed selenium, boron, and arsenic, alone or in combinations of selenium plus boron or arsenic (D.J. Hoffman, unpublished data). Protein restrictions also were imposed as an additional stress on some of the ducklings receiving selenium. Low protein in the diet intensified the toxic effects of selenium at 15 and 60 ppm. Boron at 1000 ppm had a synergistic (worsening) effect on the toxicity of 15 ppm selenium and low protein (Hoffman et al., in review). At 60 ppm selenium and low protein there was 100 percent mortality of ducklings; when 1000 ppm boron was added to selenium and low protein, mortality was again 100 percent. Arsenic at 200 ppm appeared to protect against the toxicity of 60 ppm selenium; by itself, 60 ppm selenium and normal protein levels resulted in 40 percent mortality, but with the addition of 200 ppm arsenic, mortality was 0 percent. Because the interactions can be so variable, it is difficult, at this time, to predict what might happen in the field when multiple drainwater contaminants are present at high levels. At Kesterson and Tulare, selenium levels apparently were able to cause reproductive failure in birds in spite of the presence of other contaminants, so complete antagonism could not have been operating.

CONCLUSIONS

The following general conclusions are based on field and laboratory research to date. They represent the best information available, but there are still many unanswered field and laboratory questions about drainwater pollution. Answers to these questions could refine and alter some of the conclusions listed below.

- Although other drainwater contaminants, such as boron, may pose a threat to wildlife, selenium appears to be the most harmful drainwater contaminant.

- Selenium was largely responsible for adverse biological effects in birds at the Kesterson Reservoir and reproductive impairment at Tulare Lake Basin.

- Selenomethionine is the most toxic form of selenium tested thus far in mallards.

- Embryos are the most sensitive life stage of birds to selenium poisoning. Protecting embryos from excessive exposure to selenium should protect young birds and adults as well.

- Based on laboratory results, a concentration of approximately 17 or more ppm selenium, on a dry-weight basis, in bird eggs is reason for great concern. Even levels as low as about 3.4 ppm, depending on its chemical form, cannot yet be dismissed as harmless.

- Food items of birds in aquatic environments should not be permitted to become contaminated with more than 4 ppm selenium on a dry weight basis.

- If avian reproduction is not a concern in an aquatic environment, but birds still winter there, survival of adult and young birds should be protected by not permitting food items to become contaminated with more than 10 ppm selenium on a dry weight basis.

- There are species differences in the toxicity of selenium to birds. Thus far, the mallard is the most sensitive species of wild bird tested in the laboratory.

- A bird would only have to feed in a heavily contaminated area for a week or two for harmful levels of selenium to build up in tissues or eggs.

- If a bird migrated from a selenium contaminated area to a clean area to breed, it is unlikely that high levels of selenium would persist in its body long enough to affect egg viability, unless it began egg laying within about two weeks.

- Drainwater contaminants can interact with each other and with environmental stresses to affect toxicity, but the interactions are case specific.

- Of the numerous trace elements mobilized by agricultural drainage, selenium is the element of greatest concern. Although arsenic, boron, and mercury may adversely affect avian health or reproduction, the ecotoxicology of selenium adequately explains most geographic and taxonomic variation in the occurrence and severity of drainage-associated wildlife losses.

- At some drainage sites, DDE continues to occur at high concentrations in bird eggs and adversely affects reproductive success. The source of the DDE, however, is not believed to be subsurface drainage water.

- Agricultural drainage water impoundments in arid environments attract large numbers of aquatic birds regardless of whether the sites are managed as multipurpose wetlands or as single-purpose waste disposal sites.

- Landscape mosaics are an important factor influencing the impact of drainage impoundments on wide-ranging species of birds such as ducks. For those species, an impoundment located within a mosaic of relatively clean wetlands, a "wet mosaic", is substantially less dangerous than an impoundment located in a "dry mosaic".

- Bird livers and eggs that average more than 10 and 3 ppm selenium, respectively, are characteristic of contamination above background levels. Based on field studies, impaired reproduction is very likely to occur at sites where bird livers and eggs average more than 30 and 20 ppm, respectively. Averages of more than 20 ppm selenium in waterbird eggs have been measured from impoundments comprising 63 percent of the pond acreage studied in the Tulare Basin.

- In the Tulare Basin, as little as 15 ppb waterborne selenium has been associated with significant adverse effects on waterbirds.

- In the Tulare Basin, elevated accumulation of selenium (i.e., above background) in waterbird eggs has been associated with drainage impoundments containing as little as 3 ppb waterborne selenium, but has not been associated with impoundments containing as much as 2.5 ppb waterborne selenium. More than 90 percent of all Tulare Basin impoundments exceed 3 ppb waterborne selenium.

RESEARCH NEEDS

Based on laboratory and field research conducted thus far, it is clear that drainwater contamination of some wetlands in the western United States is a major threat to waterfowl and other birds. Given the trend toward irrigation and drainwater removal in many parts of the western United States and the occurrence of soils rich in selenium, arsenic, boron, and other potential contaminants in several of these areas, drainwater hazards to wildlife are going to continue to be a problem.

Additional field and laboratory research is needed to better understand drainwater pollution. Enhancing our ability to predict when harm from drainwater contaminants will occur will translate into an increased ability of resource managers to prevent harm.

Field and laboratory studies to date have shown where there are gaps in our knowledge about drainwater contaminants. The list of research needs that follows is based on these gaps. The needs are divided into two categories: "High Priority" and "Other Research Needs". Those listed as high priority represent critical gaps in our knowledge; failure to answer these needs will mean that setting safe guidelines on drainwater contaminants will continue to be a matter of approximate answers. Those listed as other research needs also represent important research questions that would help refine guidelines for protecting wildlife from drainwater hazards. Within each category, no significance should be attached to the order in which the needs are listed.

High Priority Research Needs

1. Determine the chemical forms of selenium in aquatic food chains.
2. Determine the chemical forms of selenium in wildlife tissues and in bird eggs.
3. Measure the toxicity of the major chemical forms of selenium to key species of wildlife and conduct laboratory studies to determine species differences in sensitivity to drainwater contaminants.
4. Compare the toxicity of biologically incorporated selenium, and other drainwater contaminants, to the purified forms fed to animals in laboratory studies.
5. Determine the net demographic significance of contaminant-induced reproductive impairment, including post-hatch mortality.
6. Determine if selenium exposure influences adult longevity via interaction with otherwise normal stresses such as migration, immune challenge, winter food deprivation, etc.
7. Determine the effects of drought on the ecotoxicology of drainage impoundments.
8. Identify environmental factors responsible for significant within-site heterogeneity of contaminant exposure among different shorebird nesting neighborhoods.
9. Conduct field assessments of chemical interaction effects.
10. Determine within-site temporal trends in contaminant risk as a function of inflow contaminant load. For example, can long-term inflow of water with 1 or 2 ppb selenium eventually lead to biological risks comparable to those associated with short-term inflow of higher selenium concentrations?
11. Determine the contaminant risks to wildlife that are associated with the reuse of drainage water on agroforestry plots.

Other Research Needs

1. Develop laboratory testing procedures that better predict effects of drainwater contaminants in the field.
2. Study the interactions of nutritional and other environmental stresses with the toxicity of drainwater contaminants.

3. Determine whether populations of animals exposed to drainwater pollution have evolved any resistance to it.

4. Conduct additional laboratory tests to measure the toxic interactions of drainwater contaminants.

5. Conduct laboratory studies to measure the effects of low levels of drainwater contaminants during periods of prolonged exposure.

6. Measure the accumulation and loss of drainwater contaminants in edible tissues of game species.

7. Study the physiological mechanisms by which selenium poisoning in wildlife takes place.

8. Determine the extent and implications of uranium bioaccumulation in food-chain organisms and in wildlife tissues.

9. Continue defining the geographic distribution and severity of contamination of wildlife and their habitats associated with agricultural drainage.

10. Continue to develop appropriate reference guidelines, including studies of waterbird reproductive performance at "selenium-normal" natural saline sinks (e.g., Soda Lake and Mono Lake, CA; Lake Abert, OR; Salt Lake, UT; etc.) and Australian drainage water impoundments.

11. Determine the efficacy of siting, design, construction, and management measures intended to minimize wildlife exposure to contaminants at drainage-water impoundments.

12. Determine the efficacy of managing landscape mosaics to minimize adverse effects of drainage-water contaminants.

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